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The structure of root systems in young woody plants under the conditions of park areas with the composite topography

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Abstract

Vegetation growing on the slopes counteracts the development of erosion processes, directly affects the improvement of soil properties, which are largely determined by the morphological structure of the root system. We studied the development and distribution of the root systems of trees and shrubs on the slopes with different steepness in a forest park in the northern environs of Kyiv (Ukraine). The method of complete excavation of plants growing under the conditions of composite topography, in the park stands employed near ravines, where the plants were exposed due to erosion, was chosen for the research. The samples of root systems of 15 trees and 5 shrubs selected from different locations of growth places were examined: under the canopy, in canopy windows, in the open space, and at the slopes of different expositions with steepness from 6° to 39°. The plants aged up to 13 years, up to 3.5 m high, with crown diameter up to 130 cm and root neck thickness up to 80 mm were selected from undergrowth and understory. The depth of penetration of the root systems into the soil and the order of their branching were measured for further studying the anti-erosion properties of root systems. The area of horizontal projection of the root system to the crown diameter ratio, the soil saturation with roots and the intensity of root system branching were determined. Numerical indicators of the spatial structure of root systems are extremely important when assessing the studied trees and shrubs.

Keywords: park planting, undergrowth, understore, soil saturation with roots, depth of soil penetration, branching intensity

Introduction

Under the conditions of a composite topography there is a real threat of emergence and development of erosion processes. Vegetation is the most active means of protecting soils from water erosion. The properties of vegetation in terms of regulating soil water regime and strengthening its mechanical ability to resist runoff and linear erosion are well studied. Many studies indicate the role of the root system of plants in soil stabilization.

The reinforcing effect of plant roots on soil leads to a kind of strengthening of the mechanical stability of the slopes and improving the hydrological properties of soil. The need to quantify the root systems of plants as a relatively new task, emphasize a number of authors, viz. Watson et al. (1999), Bischetti et al. (2005, 2009), Di Iorio et al. (2005), De Baets et al. (2007) and others.

The neccesity for additional information on the development and distribution of plant roots in different soil and environmental conditions is obvious to forestry (Böhm 1979).

Information on plant growth on slopes is also important for engineering landslide prevention, as thick roots act as nails and their spatial position determines the location of the associated thin roots. Regarding soil fixation by plant roots, the most important parameter to consider is the depth of rooting (Stokes et al. 2009).

Chiatante et al. (2003) note that the function of the taproot in the consolidation of the plant over time decreases with increasing role of lateral roots, which is characteristic of both deciduous and coniferous species. Therefore, research on the fixation of plants should focus on the entire root system.

Studying the dependence of the root system on the thickness of the humus horizon, Baitulin (1987) emphasized that under conditions with a shallow humus horizon, the main mass of roots (from 85 to 95%) is localized in the upper 9–12 cm of soil. The binding and bonding effects of plant root systems on soil also depends on the intensity of development of lateral roots, the power of additional roots, the depth of penetration of roots into soil.

It is known that the structure of forest soils is observed to a much greater depth than soils that were not subject to the influence of forests (Kalinichenko and Ilinskii 1976, Kalinin et al. 1998, Maliuha and Khryk 2010, Yukhnovskyi et al. 2013).

The study of the morphological structure of roots as a system is of research interest since it is of great importance in understanding of improvement of soil properties and fertility, as well as in the exchange of substances and energy between vegetation and soil (Zhao et al. 2012).

The direction of growth of plant roots is significant in stabilizing the weathering of soil particles on a steep slope. In turn, the steepness of the slope affects the architecture of the root systems of woody plants. In this case, important characteristics of the architecture of root systems are the volume, diameter, length, quantity, spatial position and order of branching of the root (Di Iorio et al. 2005).

The mechanical effect of root systems on the soil is manifested by the depth of penetration (Böhm 1979, Danjon et al. 2008, Stokes et al. 2009, Li et al. 2017); soil saturation with roots of tree and shrub plant species (Terebukha 1971, Pylypenko et al. 2010, 2019); the peculiarity of their morphological structure and anti-erosion properties, which manifest themselves through the ratio of the horizontal projection of the root system to the horizontal projection of the crown (Kalinin et al. 1998, Maliuha and Khryk 2010, Zhao et al. 2012 and others).

The aim of the work was to obtain quantitative data on the spatial structure of the root systems of trees and shrubs of park plantations that develop in conditions of complex terrain.

Materials and methods

The study was conducted in the stands of the northern part of the Holosiivo National Nature Park, which is situated within the Kyiv Forest Plateau. The Holosiivo Forest tract is located here together with the adjacent Holosiivo Park (*or* 'Maksym Rylskyi' Park of Recreation and Leisure). The park area belongs to the Forest-Steppe zone by the character of natural complexes. GPS coordinates of the central entrance to the Park are: N 50.389263, E 30.498917.

Table 1. Classification of slopes by steepness (Pylypenko et al. 2019)

Location and shape of a slope	Slope steepness, degree	Slope steepness, %	Erosion processes
Aslope			Flushing only eluvial particles
- slightly aslope	0–3	0.0–5.2	
- medium aslope	3–5	5.2–8.8	
Slopingly			Flushing and washout of soil
- slightly sloping	5–10	8.8–17.6	
- medium sloping	10–15	17.6–26.8	
- strongly sloping	15–20	26.8–36.0	
Steep			Flushing, washout, rolling under the action of gravity
- medium steep	20–30	36.0–58.0	
- strongly steep	30–45	58.0–100.0	
Precipice (steep)	> 45	> 100	Flushing, washout, rolling and crumbling of soil

The area of the park is divided by deep ravines and gullies at the bottom of which brooks forming lakes and ponds downstream are flowing. Elevations reach up to 185–190 m a.s.l. BES. According to the classification of slopes, which considers the shape, steepness and nature of erosion processes (Table 1), the area along Holosiivskyi Avenue has mostly weak and gentle slopes. In the south-western part of the park, ravine-gully relief forms with steep slopes predominate. Most of the area is characterized by medium slopes, in the tops by steep places.

The steepness of each slope was determined from the topographic map, the fragment of which is depicted in Figure 1. We also used an eclimeter (brand, model, manufacturer) to control topographic measurements of maps.

Ravine-gully forms are developed in the Holosiivo tract. More than 90% of the area is occupied by age-old oak and hornbeam forests. Sod-slightly podzolic and gray forest soils predominate in the park (Nesterov 2007).

The park area with the manifestation of erosion processes in the form of flushing and washout, which leads to potholes and deep ravines, was examined. The locations of the studied plants growing on the complex terrain of the park area are shown in Figure 1. The root systems of plants that form undergrowth and understore and with their action increase hydraulic roughness, which is extremely important in the anti-erosion relation on complex relief, have been studied. The study of plant root systems was carried out in three locations: under the canopy of park plantings, in the windows of the canopy and in the open space. The canopy window is a clearing (opening), the length of which is equal to the average diameter of the horizontal projection of the crown of dominant trees, and the width does not exceed half the height of the stand (Pylypenko et al. 2010).

Understanding the importance of all the functions inherent in root systems, research focuses on the study of their spatial structure, which depends on the manifestation of erosion control properties of vegetation. The plants aged up to 13 years, up to 3.5 m in height with crown diameter up to 130 cm and root neck thickness up to 80 mm were selected from undergrowth and understore. The age of plants was determined by counting annual rings on the sections of trunks near the root collar.

The study of root systems was carried out according to the methods presented by Rozhkov et al. (2008). Excavation of root systems of experimental plants from park plantings was conducted near ravines, where they were exposed due to erosion (Figure 2).

After complete excavation of all roots from tree trunks to the growth ends of each root (Böhm 1979, Kalinin 1983, Chiatante et al. 2003), vertical and horizontal projections were made with the aid of ArchiCAD 23 graphical software package (Graphisoft 2019) at a scale of 1:1. During the graphic construction the places of plant growth, speed and exposure of slopes, maximum depth of penetration of the taproot into the soil, its shape and changes with depth, branching intensity, and nature of lateral roots placement were taken into account.

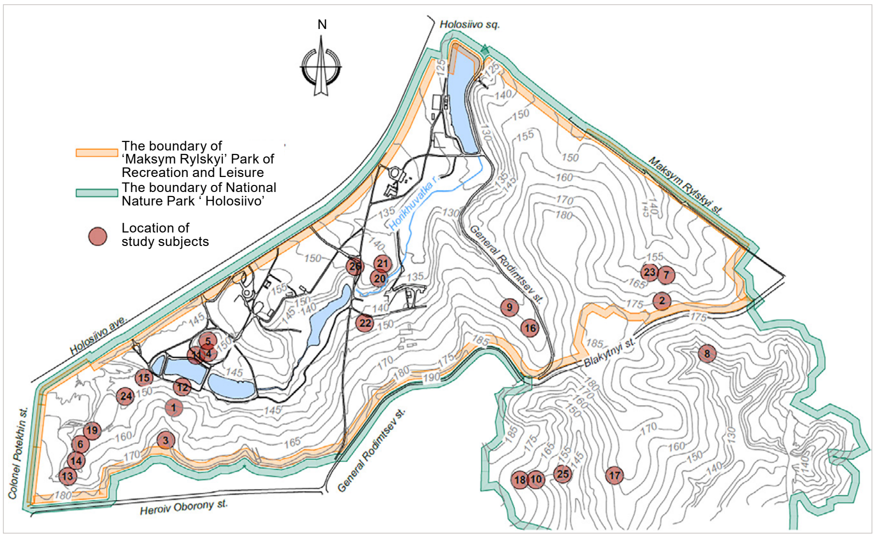

Figure 1. Map of the location of growth sites of the studied plants

The area of the horizontal projection of the root system to the area of the horizontal projection of the crown ratio, as proposed by Kalinin et al. (1998), was detected. The area of the horizontal surfaces of the crown and root system were determined based on their horizontal projections built with the aid of ArchiCAD 23 software package.

Soil saturation with roots was defined by the equation below:

$$H_s = \frac{V_r}{V_s \cdot 100\%} \qquad (1)$$

where
H_s – the saturation of the soil with roots, %;
V_r – the volume of roots in a given volume of soil, cm^3;
V_s –the soil volume, cm^3.

Soil volume is defined as the volume of spatial nutrition of the root system (Kalinin et al. 1998), which is conventionally taken to be the shape of a cone based on its horizontal projection and depth of penetration of the main root. The volume of root systems of plants according to the depth of penetration into the soil was defined according to the classification developed by Baitulin (1987) as follows: ultra-deep pattern (deeper than 10 m), very deep pattern (7–10 m), deep pattern (4–7 m), moderately deep pattern (2.5–4 m), medium pattern (1.5–2.5 m), shallow pattern (0.8–1.5 m), superficial pattern (0.4–0.8 m) and near-surface pattern (less than 0.4 m). The branching intensity was defined as the ratio of the length of the lateral roots of the first order to the length of the main root from which they come out (Baitulin 1987). At intensities less than 0.1, branching pattern should be considered as very rare; 0.1–0.5 as rare; 0.5–1.0 as weak; 1.0–2.0 as loose; 2.0–3.0 as average; 3.0–5.0 as compact; 5.0–10.0 as abundant; 10.0–20.0 as dense and more than 20.0 as a very dense pattern. The limit of formation of lateral roots of higher orders is an indicator of branching degree. In the formation of lateral roots of only the first order, the degree of branching should be considered as low, the second and third orders as medium, the fourth and fifth orders as high and the sixth and seventh orders as very high.

The average biometric values of X and their error, m, were calculated using STATISTICA 8.0 software package (StatSoft 2007, Borovikov 2013) and the significance of the difference between the means of obtained data was evaluated using Student's t-test.

Figure 2. The plants of the park stand in shade windows: *a* – a black elder (*Sambucus nigra*) on an erosion patch, *b* – a hornbeam (*Carpinus betulus*) on the edge of a ravine, *c* – a Norway maple (*Acer platanoides*) on the slope

Results

Under the canopy of the park stands under the conditions of complex terrain with a slope steepness of 7–26°, 27 root systems of 9 species of arboreal and shrubby plants aged up to 11 years were studied. The main research results are presented in Table 2.

The root system horizontal projection area to the crown horizontal projection area ratio indicates the presence of 6 species with a smaller horizontal projection area of the root system than the horizontal projection area of the crown. These are the following: *Acer platanoides* L., *Carpinus betulus* L., *Crataegus monogyna* Jacq., *Quercus robur* L. and *Tilia platyphyllos* Scop. The differences of root system HPA to crown HPA ratio between the listed species in comparison with *Acer campestre* L. were significant (t_p = 3.7–4.9). The values of the areas were the same in *Quercus rubra* L. The root system HPA exceeds the crown HPA in *Acer campestre* L. and *Euonymus verrucosa* Scop.

The highest values of this parameter (on average of 1.1 and 1.8) were revealed on strongly inclined slopes, and the smallest ones (on average of 0.5 and 0.6) on low-inclined slopes, i.e., under conditions of complex terrain that stimulate plants to develop a larger root system against the crown.

Almost all types of woody plants grown under the canopy of the park stands in the settings of complex terrain have a shallow root system. The soil of the study area is saturated with roots within 1.6–2.3% (t_p = 0.4–1.8).

Exceptions were found out in *Crataegus monogyna* Jacq., where the average root saturation is 0.9% (t_p = 2.9). The depth of penetration of the root system into soil covers the range from 10 ± 3.1 cm (*Lonicera tatarica* L., aged 3 years) to 26 ± 14.5 cm (*Crataegus monogyna* Jacq., aged 7 years). Only a specimen of *Crataegus monogyna* Jacq. at the age of 6 years, growing on the middle part of the slope of the southern exposition with a steepness of 26°, developed a surface root system (Figure 3).

The structure of root systems is presented in Figure 3: *Crataegus monogyna* Jacq.: aged 6 years, with a height of 110 cm; *Quercus rubra* L.: aged 7 years, with a height of 105 cm and *Lonicera tatarica* L.: aged 3 years, with a height of 65 cm.

Thus, there is reason to state that under the canopy of the park stands certain objective conditions in the formation of the structure of the root systems of the plants were found out. From the standpoint of erosion control, the root systems of *Quercus rubra* L. and *Lonicera tatarica* L. have a better structure than the root system of *Crataegus monogyna* Jacq.

The studied tree species show mainly 3–4 orders of root system branching that are corresponding to medium and high degrees of branching (Figure 3). *Acer campestre* L. (4.7), *Quercus rubra* L. (4.9), *Tilia platyphyllos* Scop. and *Lonicera tatarica* L. (3.9) are distinguished by dense branching of the root systems (4.7), characterizing them as the prospective species for applying in erosion control.

Table 2. Structure of root systems of wood and shrub plants growing under the canopy of park stands

Ser. No	Species	Age, yrs	Steepness, deg.	The root system HPA to the crown HPA ratio, $X \pm m$ / t_p	Parameters of root system: saturation of soil with roots, % $X \pm m$ / t_p	depth of penetration into soil, cm $X \pm m$ / t_p	intensity of branching, $X \pm m$ / t_p	order of branching
				Tree species				
1	*Acer campestre* L.	8–11	15	1.8 ± 0.20 –	1.6 ± 0.22 –	8 ± 1.3 –	4.7 ± 0.24 –	3–4
2	*Acer platanoides* L.	6–8	16	0.7 ± 0.12 4.7	1.8 ± 0.25 1.8	24 ± 4.2 1.4	2.7 ± 0.22 6.1	3–4
3	*Carpinus betulus* L.	4–6	15	0.9 ± 0.11 4.0	1.9 ± 0.24 0.9	11 ± 2.4 2.6	2.6 ± 0.11 8.0	4–5
4	*Crataegus monogyna* Jacq.	6–7	26	0.6 ± 0.23 3.9	0.9 ± 0.11 2.9	26 ± 4.5 1.7	0.9 ± 0.30 9.9	3
5	*Quercus robur* L.	1–3	25	0.7 ± 0.22 3.7	1.8 ± 0.32 1.8	14 ± 3.0 1.2	2.7 ± 0.13 7.3	3–4
6	*Quercus rubra* L.	3–7	15–26	1.0 ± 0.31 2.2	1.8 ± 0.44 0.4	17 ± 3.1 0.3	4.9 ± 0.22 0.6	3–4
7	*Tilia platyphyllos* Scop.	7–8	12–15	0.6 ± 0.14 4.9	1.7 ± 0.12 0.4	16 ± 2.2 0.8	4.7 ± 0.45 0	4
				Shrub species				
8	*Euonymus verrucosa* Scop.	2-5	20	1.1 ± 0.25 –	1.8 ± 0.40 –	13 ± 1.4 –	1.5 ± 0.73 –	3–5
9	*Lonicera tatarica* L.	3	7	0.5 ± 0.22 1.8	2.3 ± 0.32 1.0	10 ± 1.1 1.7	3.9 ± 0.46 2.8	3–4

Note: HPA – Horizontal Projection Area, cm^2; X – the average value of the studied characteristic; m – the error of the average value; t_p – a tabular value of the quintiles of the Student's t-test (t) at a probability level of 0.05, equal to 2.3.

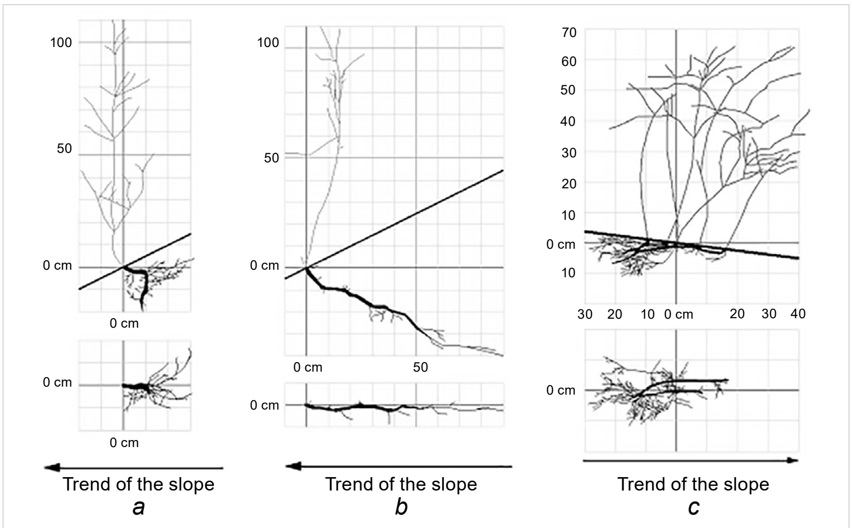

Figure 3. Projections of the root systems of the plants grown under the tree canopy: *a* – *Quercus rubra* L.; *b* – *Crataegus monogyna* Jacq.; *c* – *Lonicera tatarica* L.

The manifestation of additional lighting in the canopy windows of the park stands under conditions of complex terrain on the development of root systems was studied based on 30 specimens of 10 species of plants aged between 3 and 13 years (Table 3).

The area of the horizontal projection of the root system to the area of the horizontal projection of the crown in *Carpinus betulus* L., *Fraxinus excelsior* L., *Ulmus pumila* L., *Corylus avellana* L. and *Euonymus verrucosa* Scop. ratio ranged from 0.6 to 0.8. The differences between the listed species in comparison with *Acer platanoides* L. were not significant (t_p = 0.5–1.7). This ratio was found to be twice as much in *Juglans regia* L. (5.6) and *Populus tremula* L. (2.1). There was an increase in the surface of the crown under conditions of growth under the canopy windows of the stand compared to the conditions of growth under the canopy in *Acer platanoides* L., *Carpinus betulus* L. and *Euonymus verrucosa* Scop.

The saturation of soil with roots in most trees ranges on average from 1.6 to 2.9% and only in *Juglans regia* L. it was 1.0 ± 0.10%. The values of Student's criterion vary between 0–1.7 that indicates no significant differences at the probability level of 0.05. The opposite pattern is observed in shrub species (t_p = 5.7–5.8). The studied specimens of plants grown in the stand windows formed near-surface root systems with a depth of penetration into soil on average from 14–20 cm in *Fraxinus excelsior* L., *Carpinus betulus* L., *Populus tremula* L., *Corylus avellana* L. and *Euonymus verrucosa* Scop. to

Table 3. The structure of the root systems of tree and shrub plants growing under the canopy windows of the park stands

Ser. No	Species	Age, yrs	Steepness, deg.	The root system HPA to the crown HPA ratio, $X \pm m$ / t_p	Parameters of root system: saturation of soil with roots, % $X \pm m$ / t_p	depth of penetration into soil, cm $X \pm m$ / t_p	intensity of branching, $X \pm m$ / t_p	order of branching
				Tree species				
10	*Acer platanoides* L.	8	12	0.4 ± 0.21 –	1.8 ± 0.35 –	22 ± 2.3 –	2.6 ± 0.20 –	5
11	*Acer tataricum* L.	3–9	26	1.2 ± 0.23 2.6	1.8 ± 0.32 0	30 ± 4.1 1.7	5.1 ± 0.74 3.3	4–5
12	*Carpinus betulus* L.	6–7	12	0.6 ± 0.32 0.5	2.0 ± 0.21 0.5	15 ± 4.4 1.4	1.9 ± 0.52 1.3	4–5
13	*Fraxinus excelsior* L.	4–6	12	0.8 ± 0.10 1.7	2.3 ± 0.12 1.4	14 ± 3.2 2.0	1.6 ± 0.12 4.3	4–5
14	*Juglans regia* L.	3–8	12–15	5.6 ± 0.45 10.5	1.0 ± 0.10 2.2	26 ± 5.1 0.7	12.2 ± 1.84 5.2	4–5
15	*Populus tremula* L.	3–5	7	2.1 ± 0.84 2.0	1.6 ± 0.22 0.5	17 ± 4.4 1.0	0.6 ± 0.20 7.1	2–4
16	*Ulmus pumila L.*	6	20	0.8 ± 0.22 1.3	2.9 ± 0.53 1.7	23 ± 4.5 0.2	4.8 ± 0.83 2.6	5
				Shrub species				
17	*Corylus avellana L.*	13	6	0.4 ± 0.10 –	3.9 ± 0.22 –	18 ± 4.3 –	11.5 ± 0.25 –	4
18	*Euonymus verrucosa Scop.*	8	20	0.6 ± 0.22 0.8	2.0 ± 0.24 5.8	20 ± 5.2 0.3	1.6 ± 0.54 16.6	4–5
19	*Sambucus nigra L.*	6–7	12–30	0.9 ± 0.11 3.4	2.2 ± 0.20 5.7	25 ± 6.1 0.9	5.4 ± 0.12 22.0	5

Note: HPA – Horizontal Projection Area, cm^2; X – the average value of the studied characteristic; m – the error of the average value; t_p – a tabular value of the quintiles of the Student's t-test (t) at a probability level of 0.05, equal to 2.3.

22–30 cm in *Acer platanoides* L., *Ulmus pumila* L., *Sambucus nigra* L., *Juglans regia* L. and *Acer tataricum* L. There was no significant difference in the penetration depth of the roots in both trees and shrubs (t_p = 0.2–2.0).

The branching of the root systems of most of the plants studied was characterized by 4–5 orders, which corresponds to a high degree of branching. The exception is such species as *Populus tremula* L. (2–4). High rates were found in 4 species, which were characterized by compact as in *Ulmus pumila* L. (4.8), abundant as in *Acer tataricum* L. (5.1) and *Sambucus nigra* L. (5.4) and dense as in *Juglans regia* L. (12.2) branching of root systems. This characterizes them as reliable species in terms of erosion control (Figure 4).

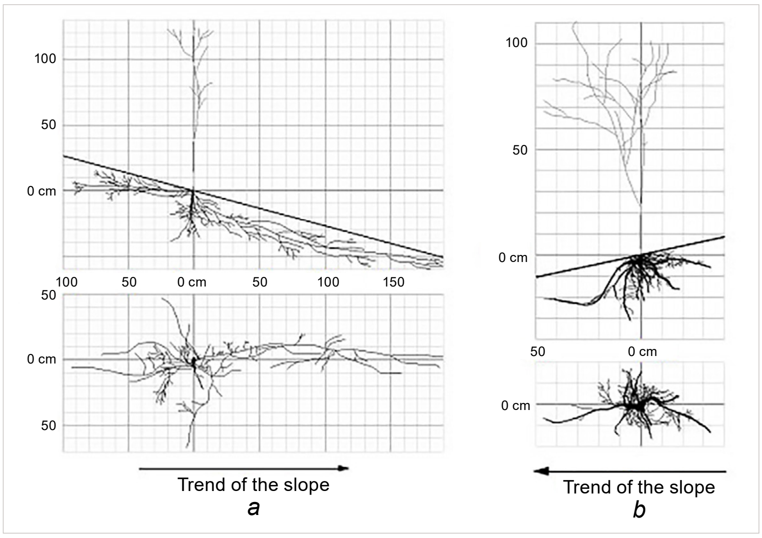

Figure 4. Projections of the root systems of the plants that have grown in the stand windows: *a – Juglans regia* L.; *b – Sambucus nigra* L.

The structures of the root systems of *Juglans regia* L. (aged 8 years, 122 cm high) and *Sambucus nigra* L. (aged 7 years, 110 cm high) are shown in Figure 4. From the given images it is visible that the root systems of the plants grown in the windows of the park plantings have a better structure than those grown under the stand canopy.

The study of root systems of woody plants growing in the open sites was conducted based on 20 specimens of 7 species aged from 3 to 10 years (Table 4).

The area of the horizontal projection of the root system to the area of the horizontal projection of the crown ratio, which is twice much, were found in 3 species of trees, viz. *Quercus robur* L. (2.2), *Salix alba* L. (6.9), *Populus tremula* L. (7.4). The rest specimens of the plants have formed a horizontal area of the root system half as much than the horizontal area of the crown.

The largest area of the horizontal projection of the root system of plant grown in the open sites is formed on gently sloping patches. Accordingly, its reduction occurs on moderate slopes, strong slopes and very strong slopes.

The depth of root penetration into soil in this group of plants increases to 190 ± 20.5 cm (*Quercus robur* L.), which corresponds to the average level (Figure 4). Shallow penetration depth of 100 ± 18.4 cm was found in *Salix alba* L. The surface root system was formed in other tree plant species, such as: *Cerasus avium* (L.) Moench., *Pop-*

Table 4. The structure of the root systems of arboreal and shrubbery plants growing in the open sites of the park stands

Ser. No	Species	Age, yrs	Steepness, deg.	The root system HPA to the crown HPA ratio, $X \pm m$ / t_p	Parameters of root system: saturation of soil with roots, % $X \pm m$ / t_p	depth of penetration into soil, cm $X \pm m$ / t_p	intensity of branching, $X \pm m$ / t_p	order of branching
				Arboreal species				
20	*Cerasus avium* (L.) Moench.	5–6	15	0.4 ± 0.22 / –	3.3 ± 0.51 / –	30 ± 6.2 / –	9.7 ± 0.22 / –	4
21	*Populus tremula* L.	3–5	6	7.4 ± 1.17 / 5.9	1.5 ± 0.28 / 3.1	50 ± 8.4 / 1.9	1.1 ± 0.10 / 35.5	4–5
22	*Pyrus communis* L.	10	18	0.2 ± 0.12 / 0.8	1.1 ± 0.20 / 4.0	65 ± 12.2 / 2.6	0.9 ± 0.35 / 21.3	3
23	*Quercus robur* L.	6–8	6	2.2 ± 0.14 / 6.9	1.9 ± 0.21 / 2.5	190 ± 20.5 / 7.5	8.6 ± 1.24 / 0.9	4–5
24	*Salix alba* L.	5	6	6.9 ± 0.52 / 11.5	1.4 ± 0.44 / 2.8	100 ± 18.4 / 3.6	1.9 ± 0.45 / 15.6	3–4
				Shrubbery species				
25	*Euonymus verrucosa* Scop.	5–8	14	0.6 ± 0.34 / –	4.4 ± 0.23 / –	27 ± 2.9 / –	16.7 ± 1.22 / –	4
26	*Juniperus sabina* L.	4	39	0.8 ± 0.18 / 0.5	5.3 ± 0.49 / 1.7	15 ± 4.5 / 2.2	12.5 ± 0.43 / 3.2	4

Note: HPA – Horizontal Projection Area, cm^2; X – the average value of the studied characteristic; m – the error of the average value; t_p – a tabular value of the quintiles of the Student's t-test (t) at a probability level of 0.05, equal to 2.3.

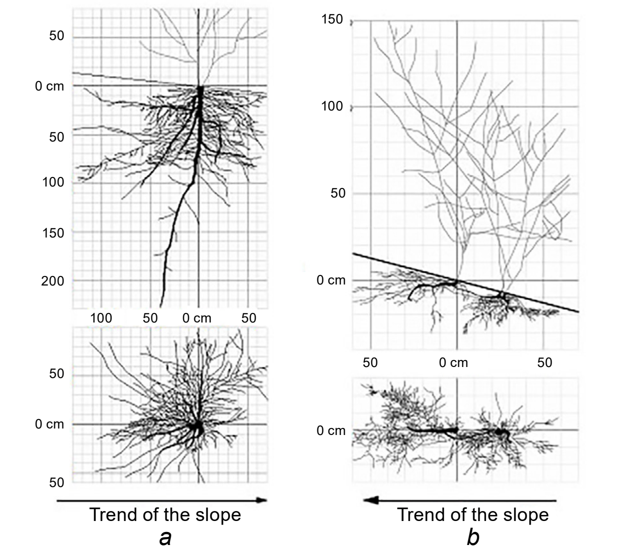

Figure 5. Projections of the root systems of the plants grown in the open sites: *a – Quercus robur* L.; *b – Euonymus verrucosa* Scop.

ulus tremula L. and *Pyrus communis* L., as well as in the shrubs (Figure 5).

The structures of the root systems of a common oak (*Quercus robur* L.; aged 8 years, 340 cm high) and 2 specimens of wartybark euonymus (*Euonymus verrucosa* Scop.; aged 8 and 5 years, and 150 and 95 cm high, respectively) are presented in Figure 5. From the given images it is visible that in the open areas of the park plantings, the formation of the structure of root systems appeared the most favourable in the absence of interspecific competition.

At open sites, the average value of soil saturation with roots for the plants grown on gentle slopes is 2.0%, on moderate slopes is 3.6%, on strong slopes is 2.2%, and on very strong slopes is 3.2%.

The order of branching of many root systems is in the range of 4–5, which, according to the classification developed by Baitulin (1987), corresponds to medium and high degrees of branching. The branching intensity of 4 species of this group of plants was defined as abundant and dense: *Quercus robur* L. (8.6 ± 1.24), *Cerasus avium* (L.) Moench. (9.7 ± 0.22), *Juniperus Sabina* L. (12.5 ± 0.43), *Euonymus verrucosa* Scop. (16.7 ± 1.22), which characterizes them as effective erosion control species.

It should be noted the general trends in the spatial structure of the root systems of the studied plants:
1) with an increase in the steepness of the slopes, the manifestation of root system asymmetry intensifies;
2) the main root buries perpendicular to the slope surface;
3) the lateral root spreads more intensively up the slope;
4) sprouts occupy space down the slope.

Discussion

The optimal conditions for the development of root systems are the conditions for the habitat of plants in space, where the horizontal projection of the root system develops at the level of the horizontal projection of the crown and wider. Such data are found in about 60% of woody plants studied. At the same time, for plants growing under the canopy and in the windows of the stands, this figure is within 40%. This confirms the data of Baitulin (1987) that plants growing in the open sites form a denser and more abundant root system, compared to those growing under the canopy or in the windows of the stands. Such a weak development and shallow penetration of the root system of plants into soil in the lower layers of forest phytocenoses are mainly due to shading by the canopy cover. Kalinin et al. (1998) note an increase in the protective functions of stands provided that the radius and the root projection area of the tree are several times greater than the radius and projection area of its crown.

According to Danjon et al. (2008), trees with root systems that have many lateral roots but no central roots may be useful for reinforcing soil at the top or at the bottom of the slope. Trees with root systems with elongated taproots better reinforce soil in the central part of the slope. These conclusions are consistent with the results of our research.

Di Iorio et al. (2005) indicate the adaptive development of root systems within slope conditions, which lead to root asymmetry. Stokes et al. (2009) in their study of direction of root growth, developing under conditions of complex terrain, claim that *Quercus cerris* L. is dominated by root growth either up or down, which improves its fixation along the axis of static mechanical load. Chiatante et al. (2003) emphasizes the specificity of asymmetric architecture of root systems because of mechanical forces acting on steep slopes. This asymmetric architecture is the result of predominant germination and elongation of lateral roots in the up and down directions. Similar changes were found by Di Iorio et al. (2005) in studies of *Quercus pubescens* growing on a steep slope, because of adaptive biomass growth on the descent becomes lower than on the upper place. Root systems demonstrate normal symmetrical architecture when the same species is grown on the flat terrain.

Regarding the assessment of the distribution of root systems in soil, the determined depth of penetration indicates its near-surface location in most of the studied plants. This is confirmed by the study of Di Iorio et al. (2005) that in fact most of the roots were found at a depth of less than 0.6 m. Bischetti et al. (2009) reports that in most cases the maximum depth of root penetration into the soil was between 0.8 and 0.9 m. Stokes et al. (2009) noted that generally, about 80% of the biomass of the root system was observed in the upper layer of soil at the depth of 0.4–0.5 m.

Most of the studied plants under the age of 13 have a medium or high degree of root branching. Conditions of composite relief encourage active branching in the root systems, so the studied specimens of *Quercus robur* L. at the age of 1–3 years already demonstrated branching of the 4th order, while according to Kalinin et al. (1998), on the plains, it reaches this branching order by the age of 10 years.

Stokes et al. (2009) and Danjon et al. (2008) note the nessecity for additional research on various plant species in terms of slope stability, given the differences in topography and ecology. To this end, it is quite useful to develop a database of species to which researchers can freely add their data (Norris et al. 2008). Our data could complement such databases. Quantitative data on the spatial structure of root systems should also be combined into a generalized conceptual model of soil reinforcement, which provides an initial opportunity to rank plant species with special rooting properties that can be used to erosion control (Watson et al. 1999). Reubens et al. (2007) offer a complete 3D description of the architecture of root systems for the development of appropriate software intending to obtain information about almost any characteristic of the root system. In this regard, in the model of soil reinforcement, data on the root systems of the studied tree species are of significant value.

Therefore, data from the studies of the spatial parameters of the roots in different plant species under different habitat conditions confirm the conclusions of Kalinin (1983), Terebukha (1971) and Minder et al. (2019) on the dependence of the structure of root systems on the steepness of the slopes.

Conclusions

Peculiarities of the structure of root systems of tree species under the conditions of complex terrain are revealed, which are first manifested in the pronounced asymmetry of the root system.

Branching in the root systems of the studied trees under 11 years of age does not exceed the 5th order. The general tendency of growth of indicators of the areas of a horizontal projection and volumes of soil foot of trees and shrubs with age remains. The horizontal projection area of root system to the horizontal projection area of crown ratio is as follows: under the canopy on average of 0.5 to 1.8; on average from 0.4 to 5.6; and in open space on average from 0.2 to 7.4. The inhibition of the development of the root systems of undergrowth and understore plants under the canopy of plantations was confirmed, in comparison with the plants growing in the windows or in the open space.

Under the canopy, the weak structure of the root systems is due to significant competition from other plants, which together counteract the emergence of erosion processes. In the open area, the development of root systems, although more intense, but single plants in the case of erosion are not able to effectively resist it.

The depth of root penetration into soil is found mainly in its upper layers up to 0.4 m: under the canopy (trees from 9 to 40 cm in height; shrubs from 7 to 15 cm in height); in the canopy windows (trees from 10 to 38 cm in height, bushes from 14 to 35 cm in height); in open areas (trees from 24 to 230 cm in height, shrubs from 11 to 30 cm in height). Soil saturation with roots was determined. For plants growing under the park stand canopy, this characteristic was recorded on average from 0.9 to 2.3%; for plants growing in canopy windows on average from 1.0 to 3.9%. Plants growing in open areas demonstrated the highest values, on average from 1.1 to 5.3%. Branching intensity is as follows: under the canopy from 0.6 to 7.2%; in canopy windows from 0.3 to 14.0% and in open areas from 0.9 to 17.5%.

The presented results will develop knowledge about the spatial distribution of roots in soils under the conditions of complex terrain. The obtained data will permit to implement models of soil reinforcement with the ranking of species of woody plants, which should be employed to provide erosion control and assess the contribution of woody vegetation to increase the resistance of soil to erosion.

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